

The crucial role of substorms and whistler-mode chorus waves in the rebuilding of Earth's radiation belts

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LANL SHIELDS meeting
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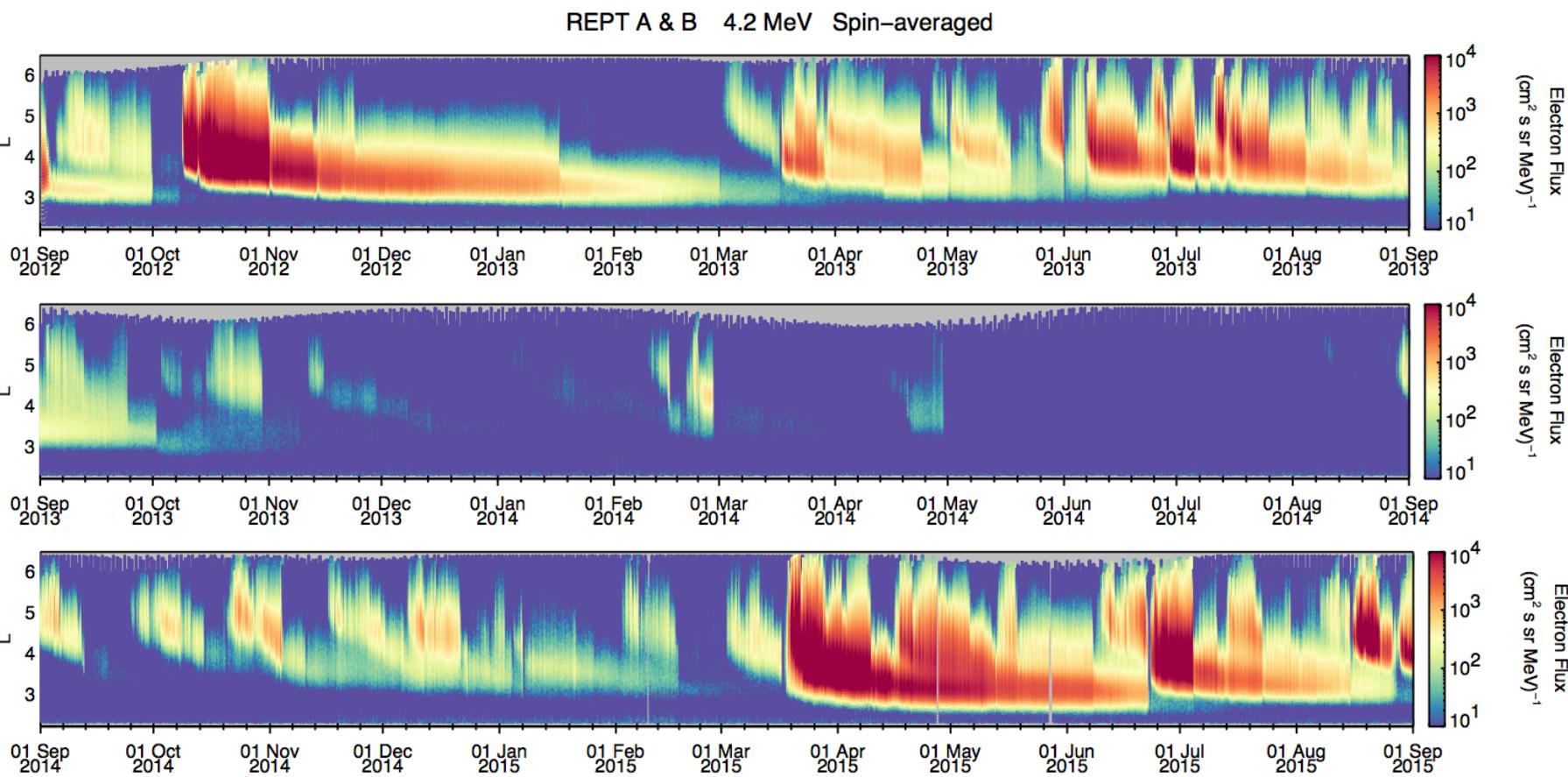
Outline

- Background: Substorms, storms, & radiation belt dynamics
 - The accelerator mechanism: source & seed particle populations
 - Sept 2014 storm study
 - Extension to long-term dynamics
 - Current seed particle studies: MMS & Van Allen Probes
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Conclusions

- VLF chorus waves are a significant generator of relativistic & ultra-relativistic electron populations in the inner magnetosphere
- Substorms (not necessarily storms) are the driver for effective acceleration events

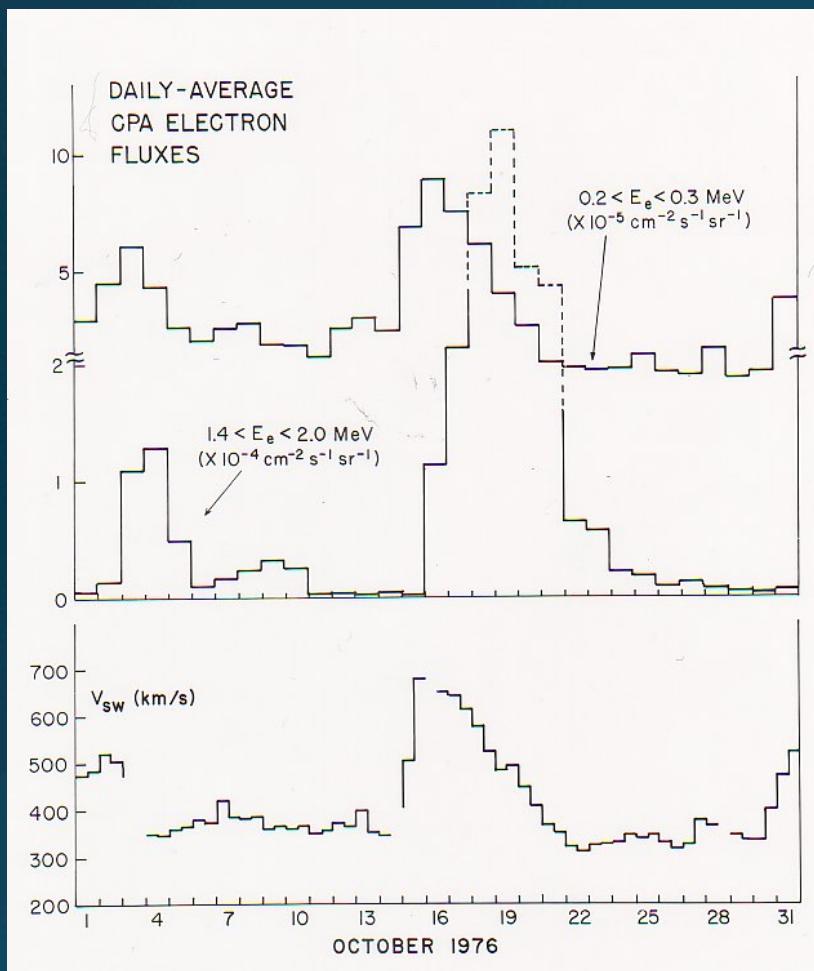
Dynamic radiation belts: 3 years



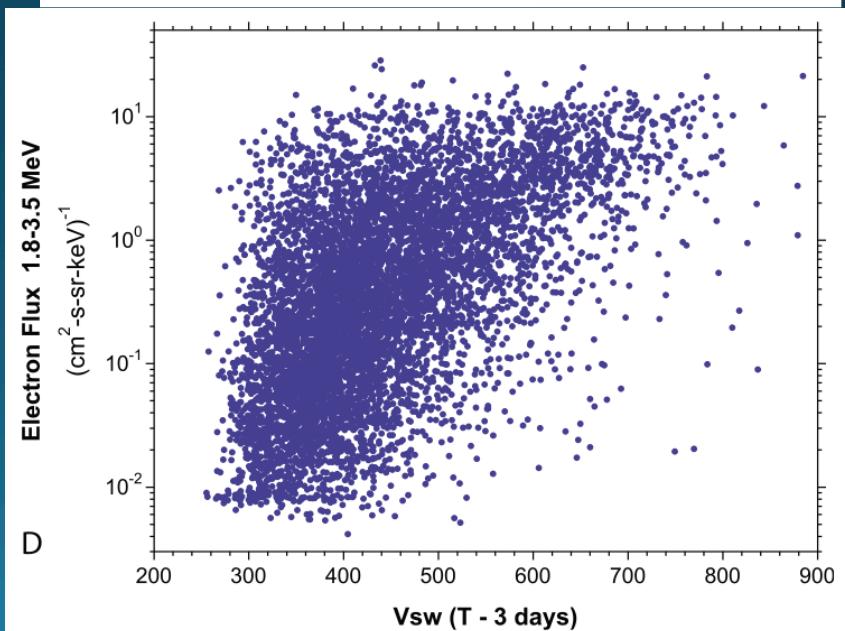
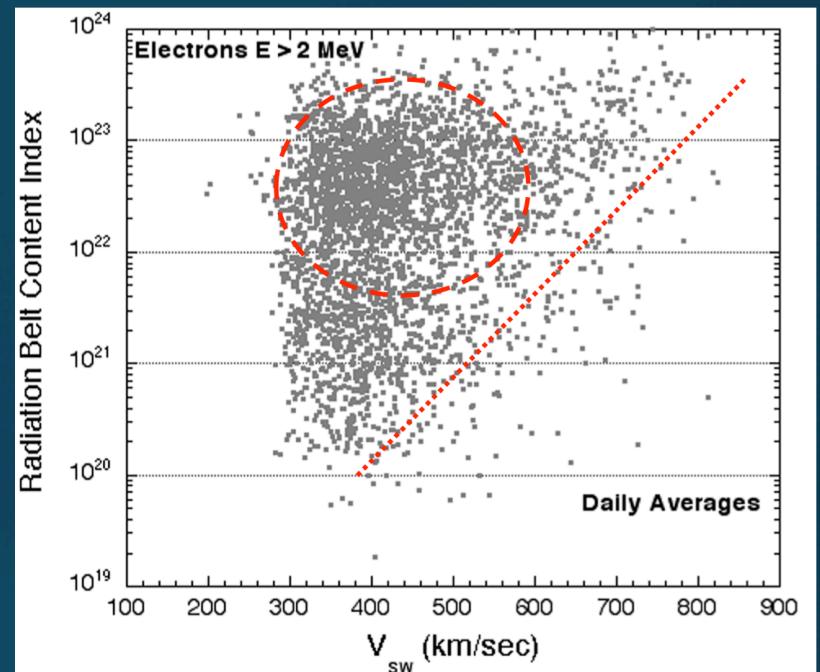
Substorms & radiation belt enhancements

Electron response to solar wind speed

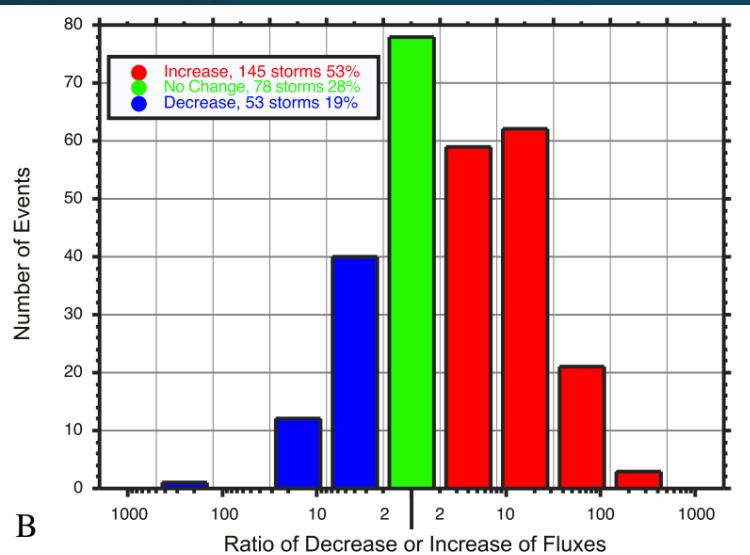
[Baker et al., JGR, 1979]



- electrons from $\sim 30\text{-}300 \text{ keV}$ (at GEO) were closely related to solar wind speed variations
- electrons $> 1 \text{ MeV}$ were found to be delayed in relation to solar wind stream profiles
- high fluxes can be produced by ANY solar wind speed



Variation in storm response

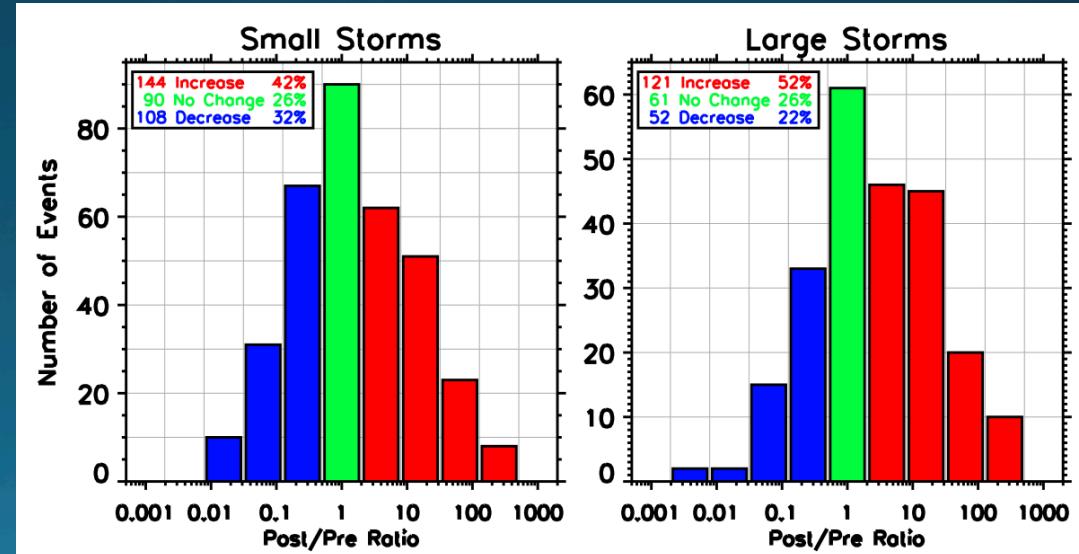


Reeves et al., GRL, 2003

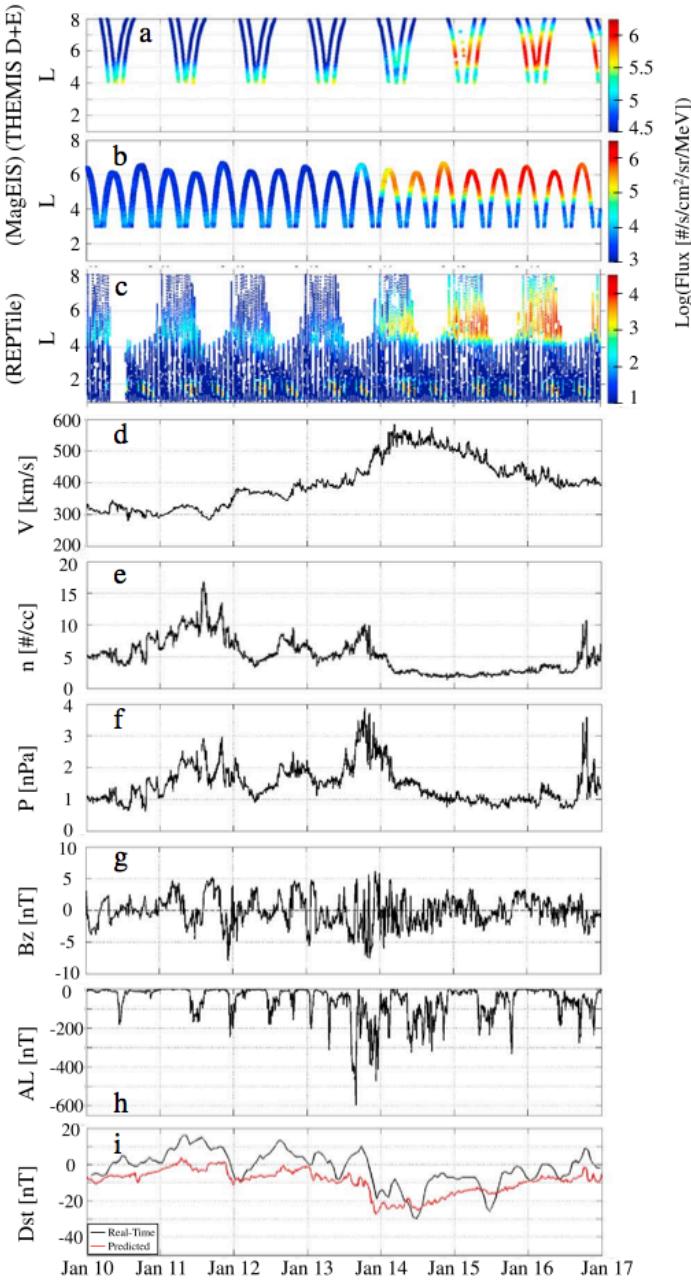
- Response of 1-3 MeV electrons in outer radiation belt over 11 years (276 storms!)
- A given storm can increase or decrease relativistic flux
- Almost no correlation between pre- and post-storm fluxes
- No relation to Dst, slight relation to solar wind speed
- If you've seen one storm, you've seen one storm

Anderson et al., GRL, 2015 (in review)

- Anderson et al. repeated Reeves 2003 study using same data set
- Small storms (> -50 nT) produce as much variation in relativistic fluxes as large storms
- Slightly less likely to enhance, slightly more likely to deplete
- Electron response does not scale with strength of storm



Nonstorm enhancements



- Schiller et al., 2014 studied nonstorm time enhancement of relativistic electrons during mid-January 2013
- Su et al., 2014 nonstorm time enhancement in late Feb 2013
- Both attributed enhancement to local heating via chorus
- Neither one emphasized the role of substorm injections, although substorm activity was high during both events
- Meredith et al., 2002 suggested that only large storms that included prolonged substorm activity could effectively enhance relativistic electrons
- Kataoka and Miyoshi, 2010 found that the main controller of outer belt electron fluxes was IMF orientation (i.e. little southward B_z = no enhancement events)

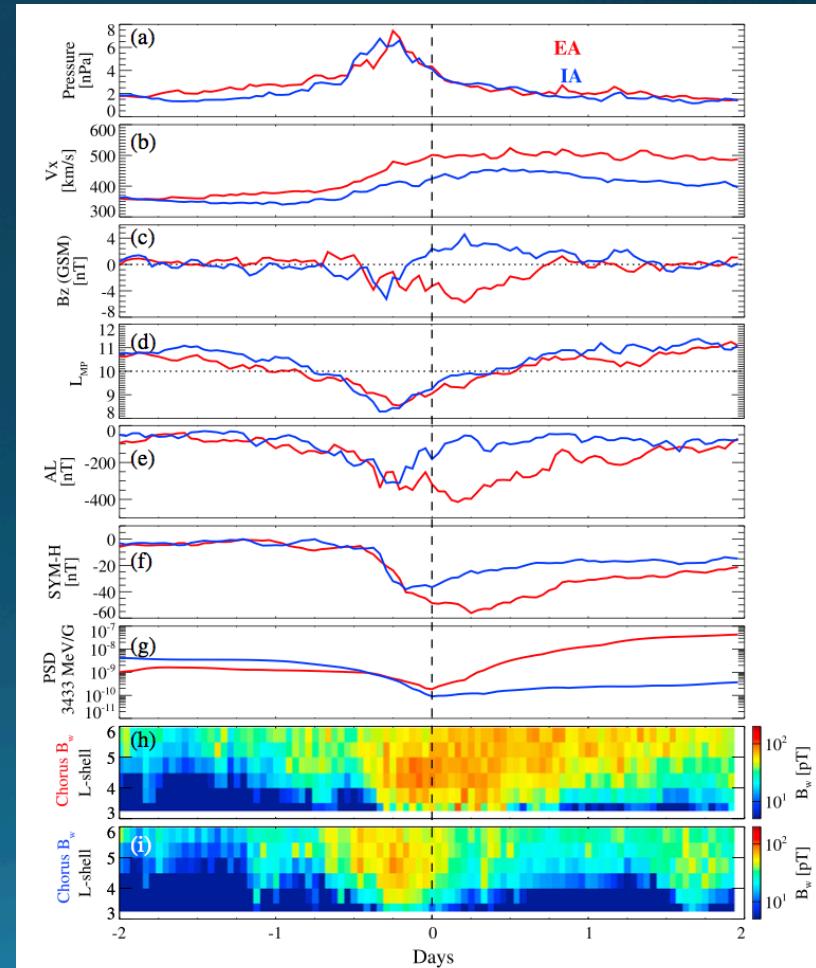
Efficient acceleration events

X. Li et al. [2011]:

- Compared modeled MeV flux at GEO with measurements
- 'a southward orientation of the IMF is a necessary condition for MeV electron enhancements at geosynchronous orbit and that high-speed solar wind are not necessary.'

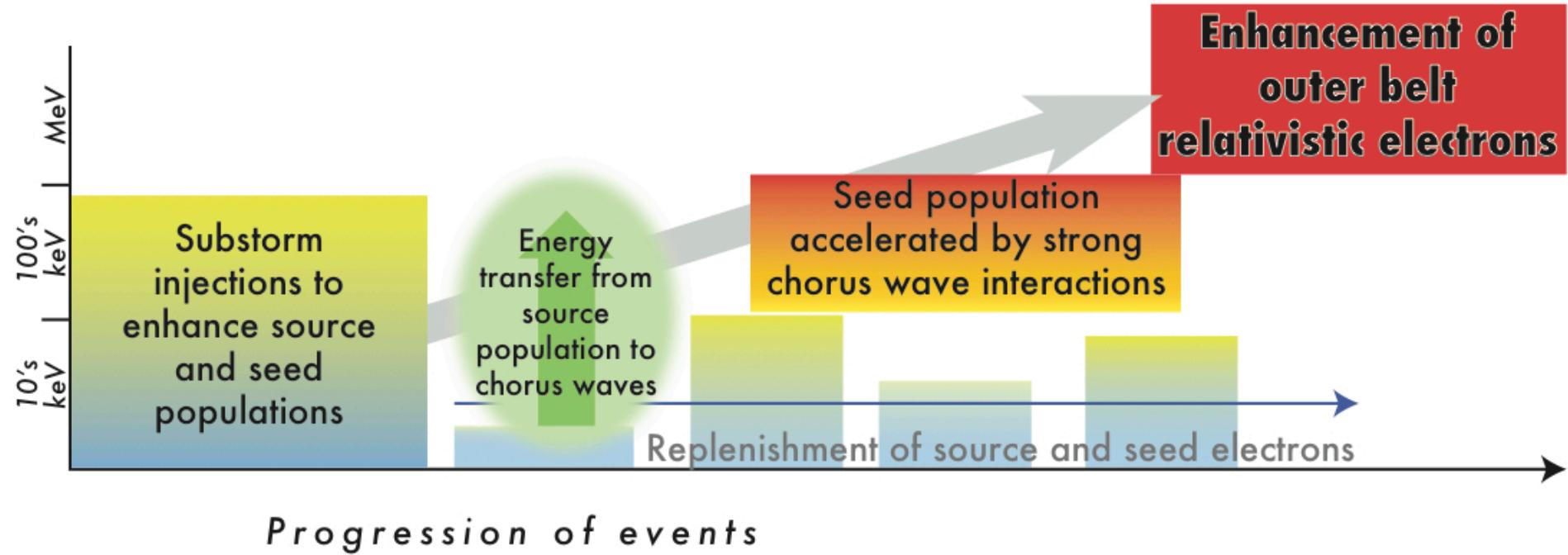
W. Li et al. [2015]:

- Superposed epoch analysis of efficient and inefficient MeV acceleration events using Van Allen Probes data
- Main contributions to efficient events:
 - Prolonged southward B_z
 - High solar wind speed
 - Low solar wind dynamic pressure
- Presence of chorus waves is most intense for longer times during efficient acceleration events



**Sept 2014: Ideal experiment set
up by nature**

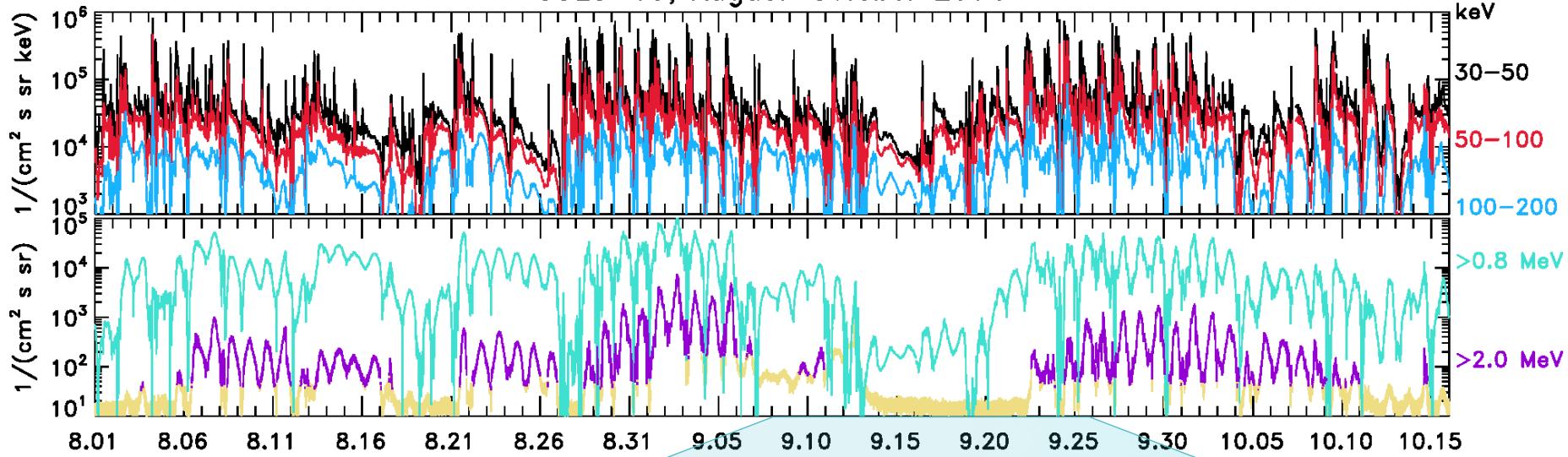
The Accelerator Mechanism in the Inner Magnetosphere



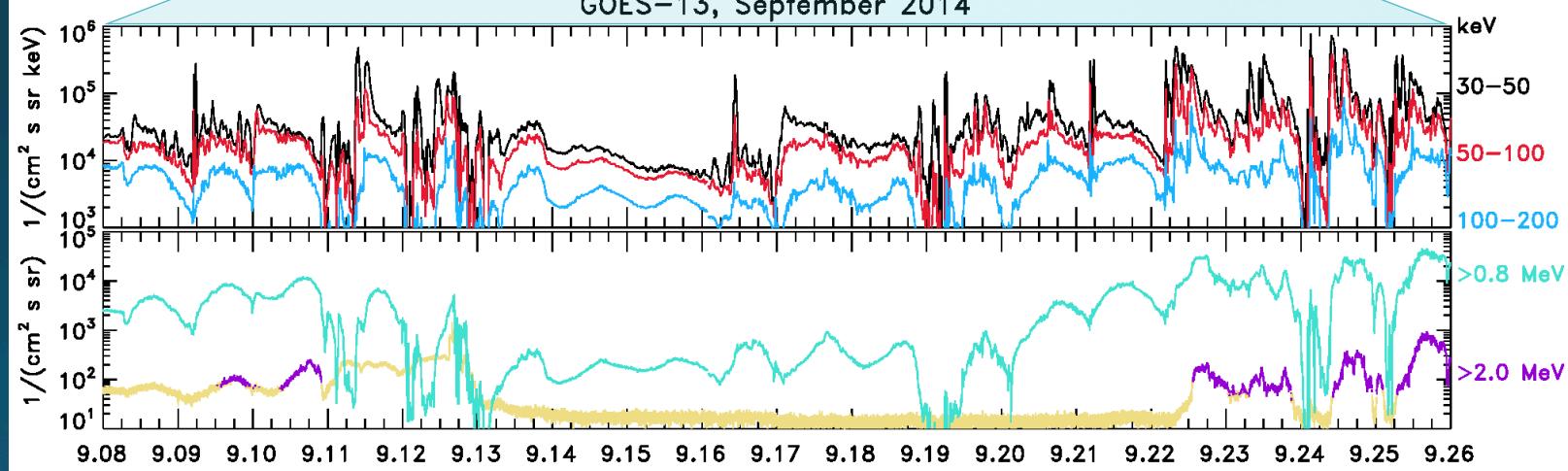
Source: several to 10's of keV
Seed: 100's of keV

Initial observations at GOES

GOES-13, August–October 2014

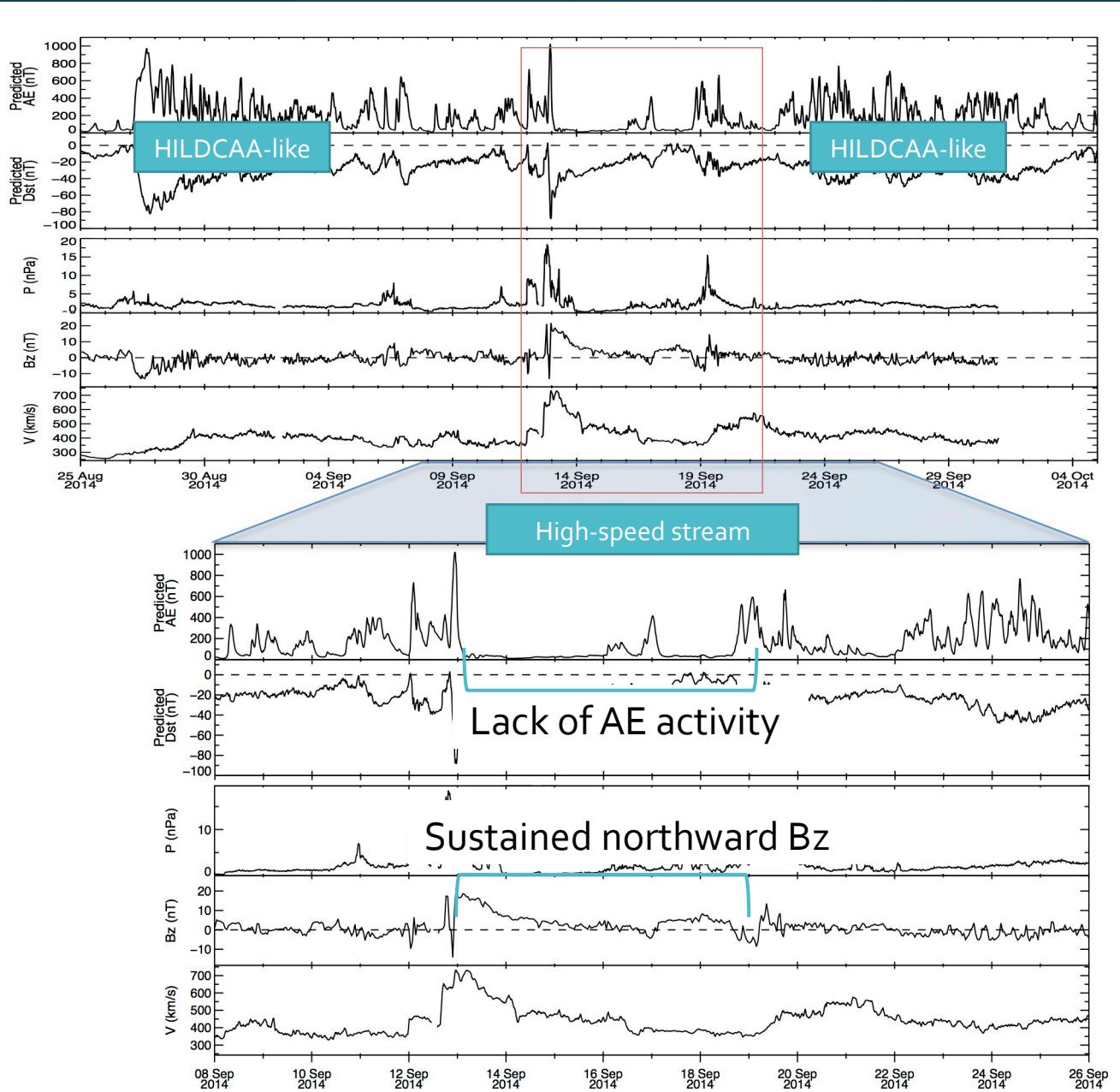


GOES-13, September 2014



Event brought to our attention by Howard Singer

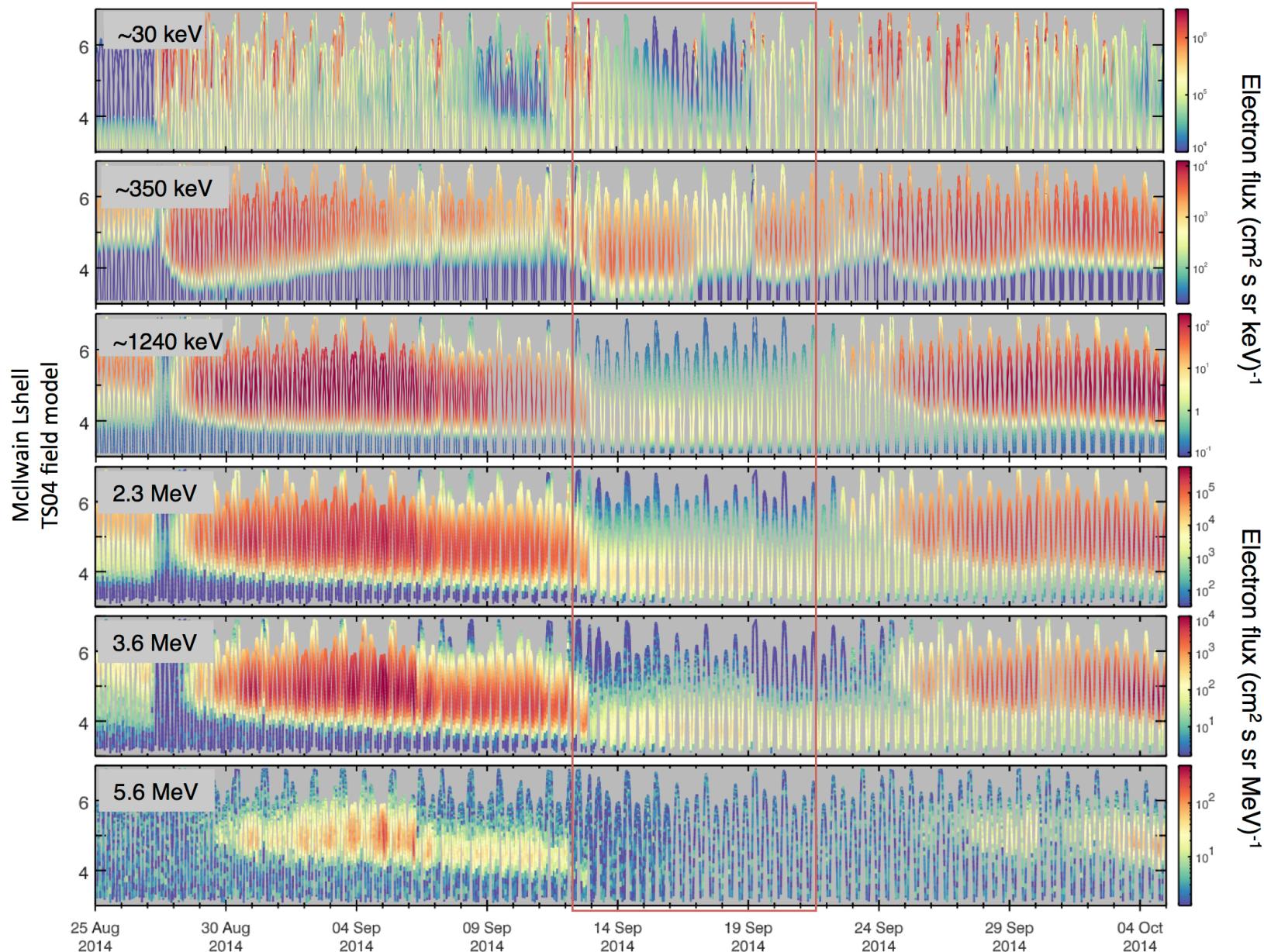
Solar wind and geomagnetic activity



Van Allen Probes Particle Observations

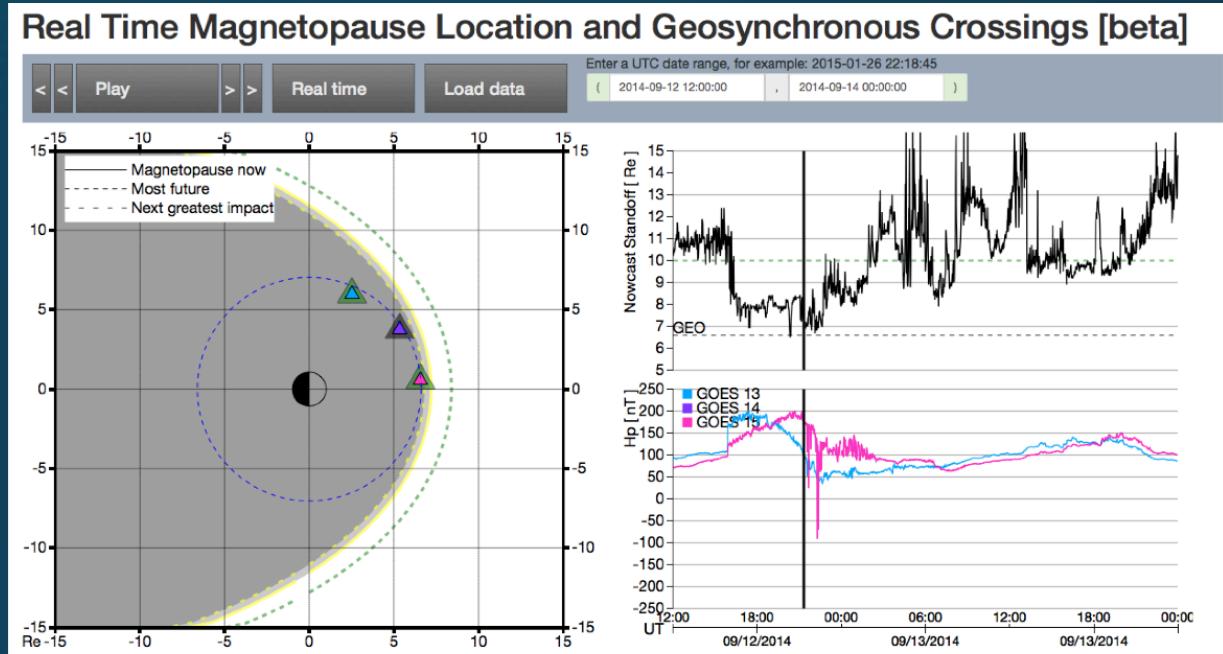
MagEIS

REPT



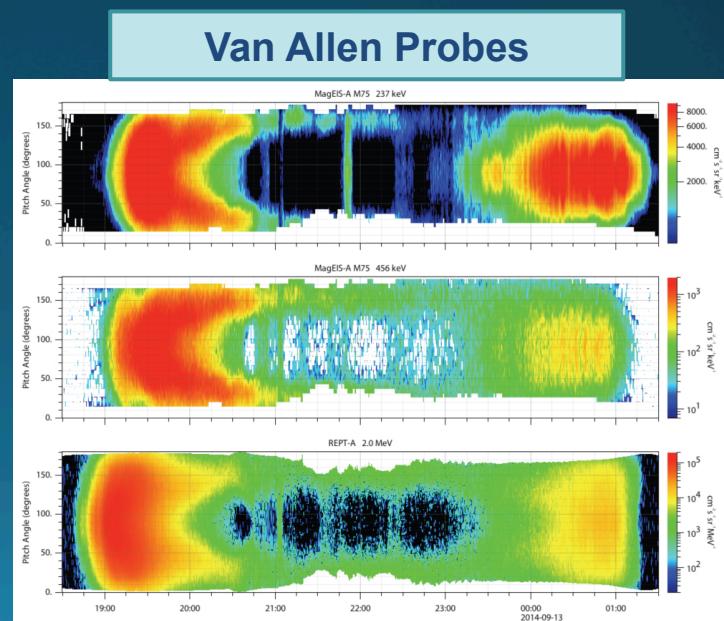
Loss via magnetopause shadowing: 12-13 September

- Magnetopause location (Shue et al. model) for Sept 12-13
- Several compressions to inside or very near GEO

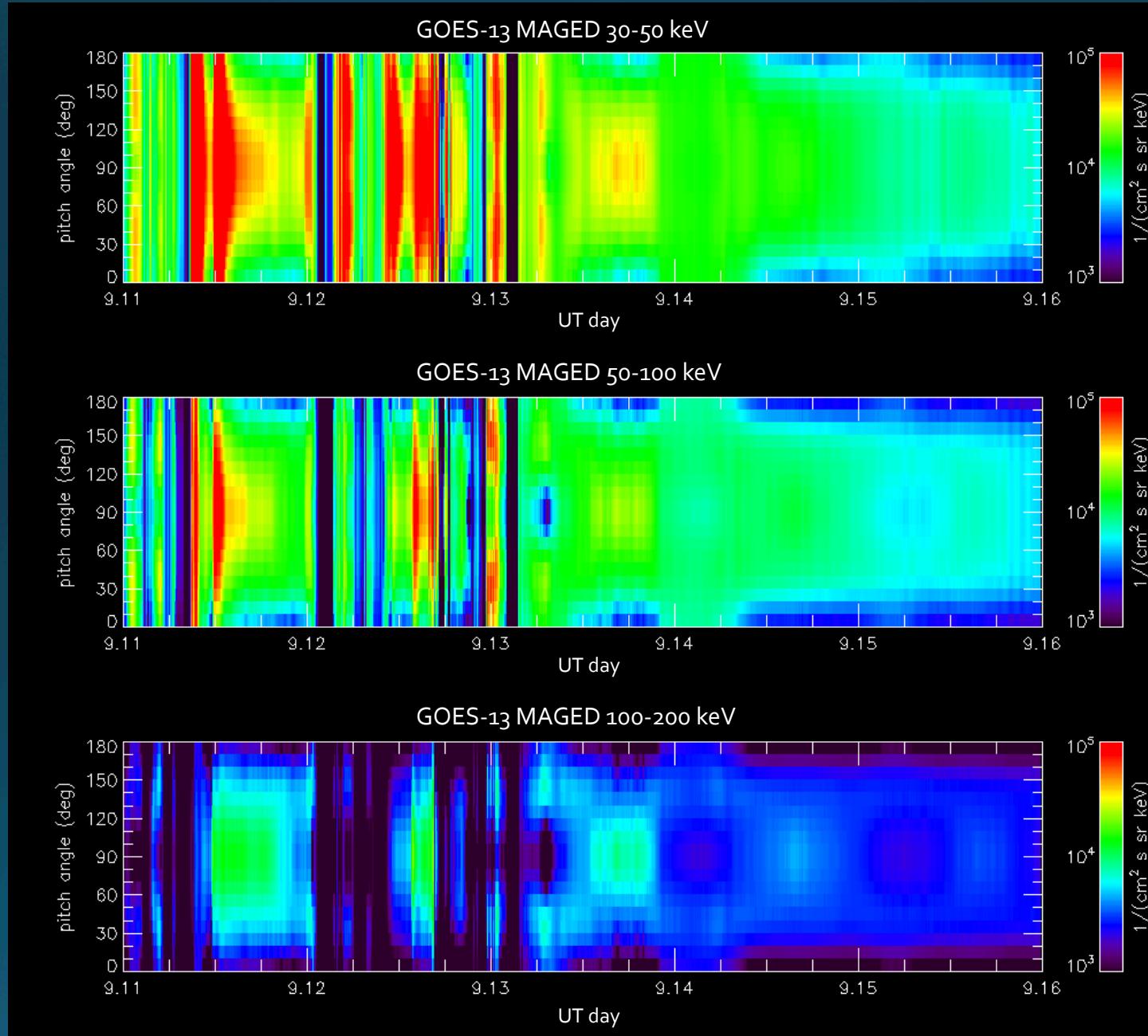


http://www.ngdc.noaa.gov/stp/mag_pause/

- Typical butterfly distribution observed at both RBSP & GOES during the point of most earthward magnetopause standoff: just inside GEO
- Energetic electrons continue to diminish over the following 24 hours and remain at low levels for days afterward

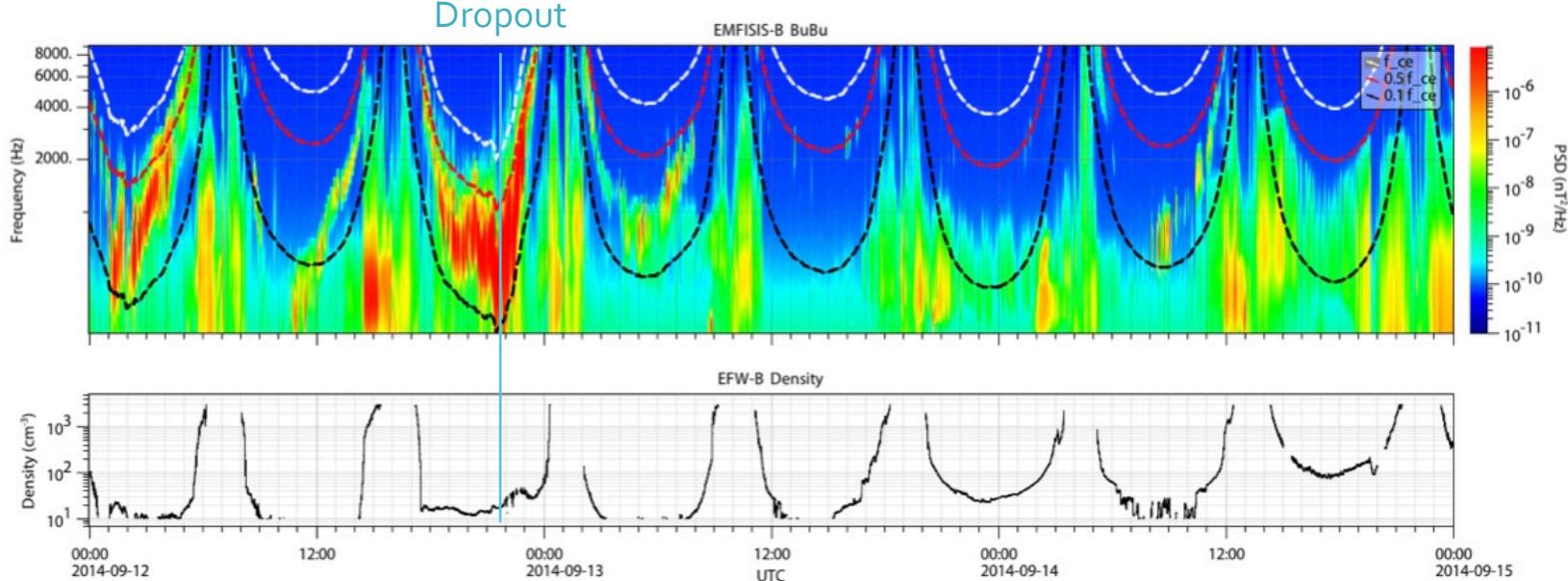


Same signature in GOES pitch angle distributions

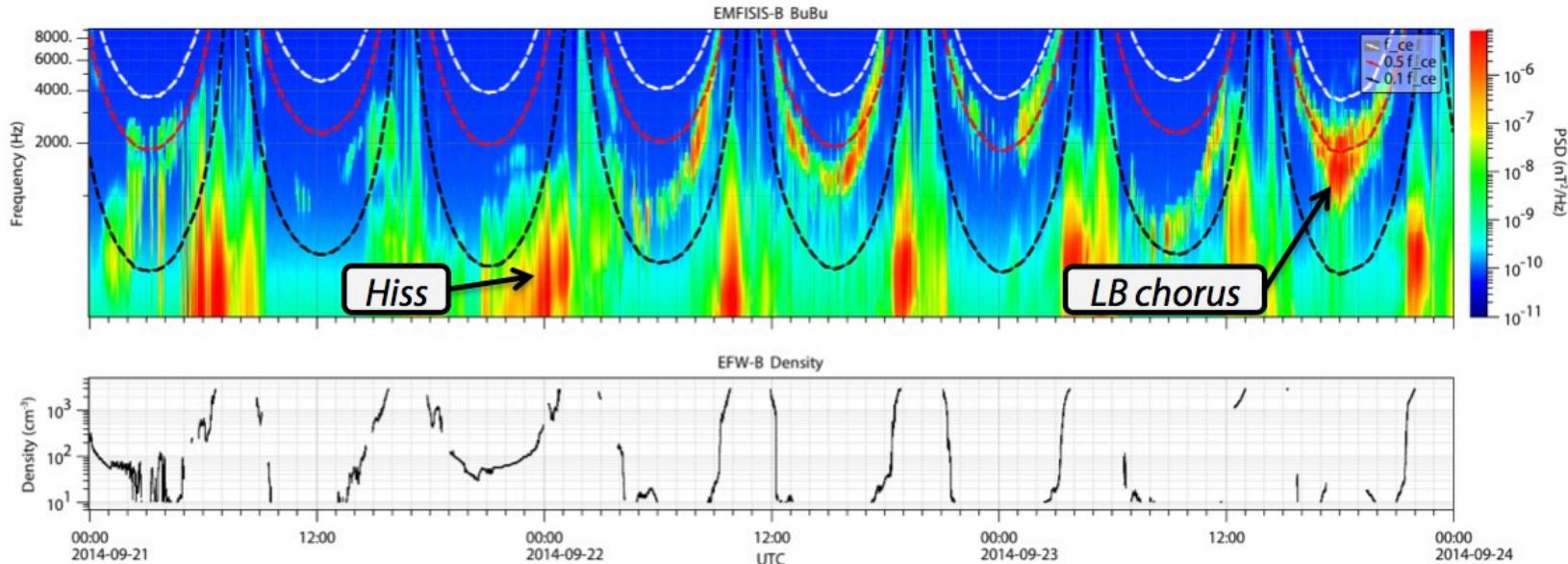


Chorus wave observations: Van Allen Probes

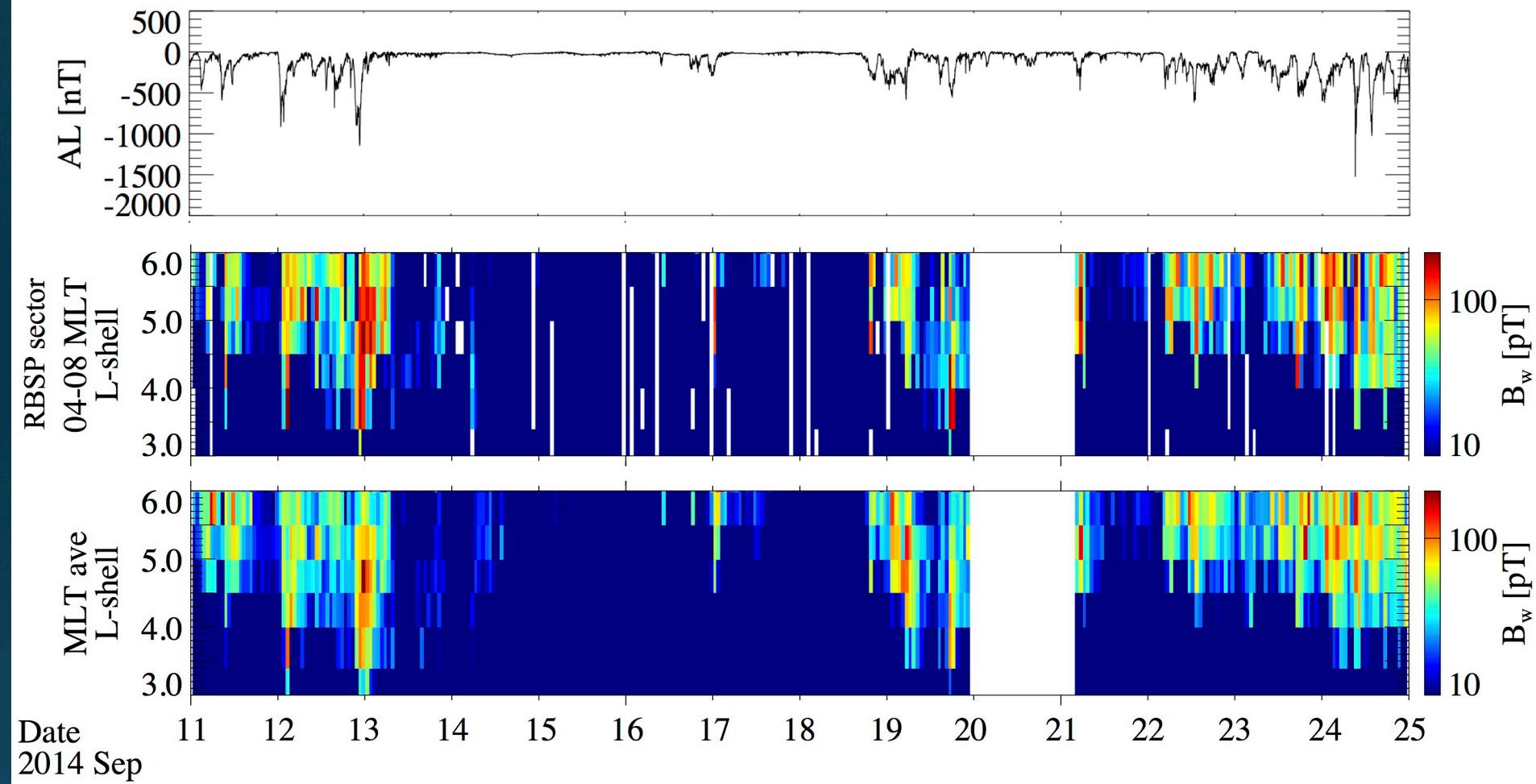
Sep 12-14
MeV loss



Sep 21-24
MeV reappearance



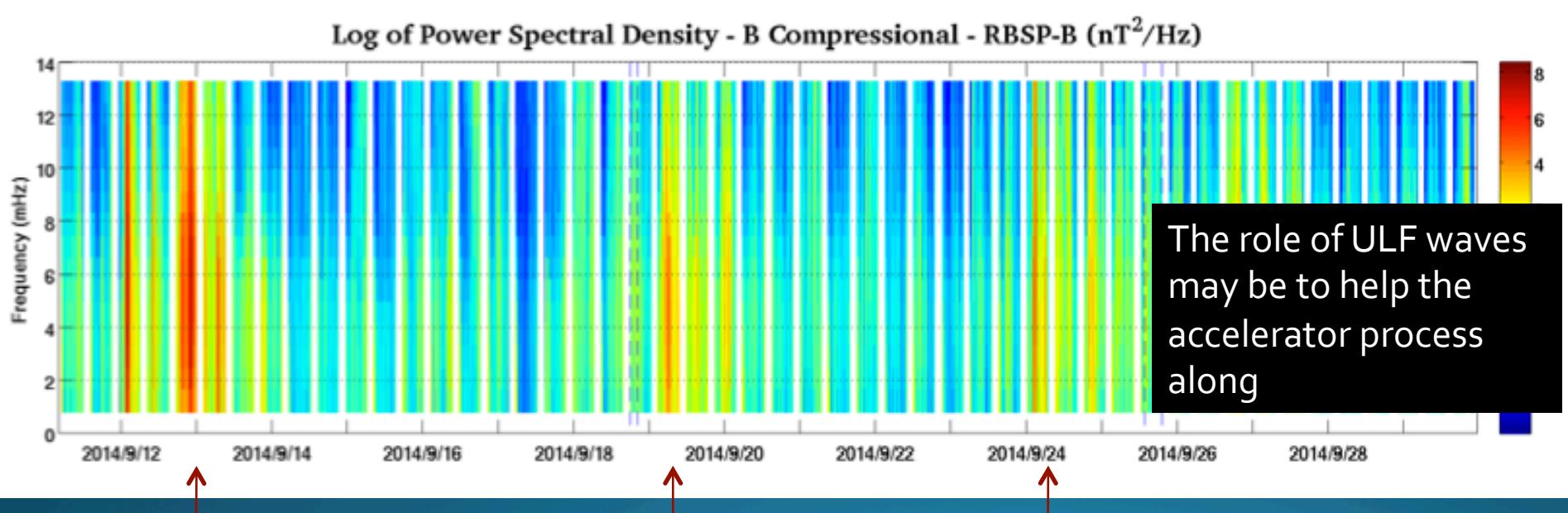
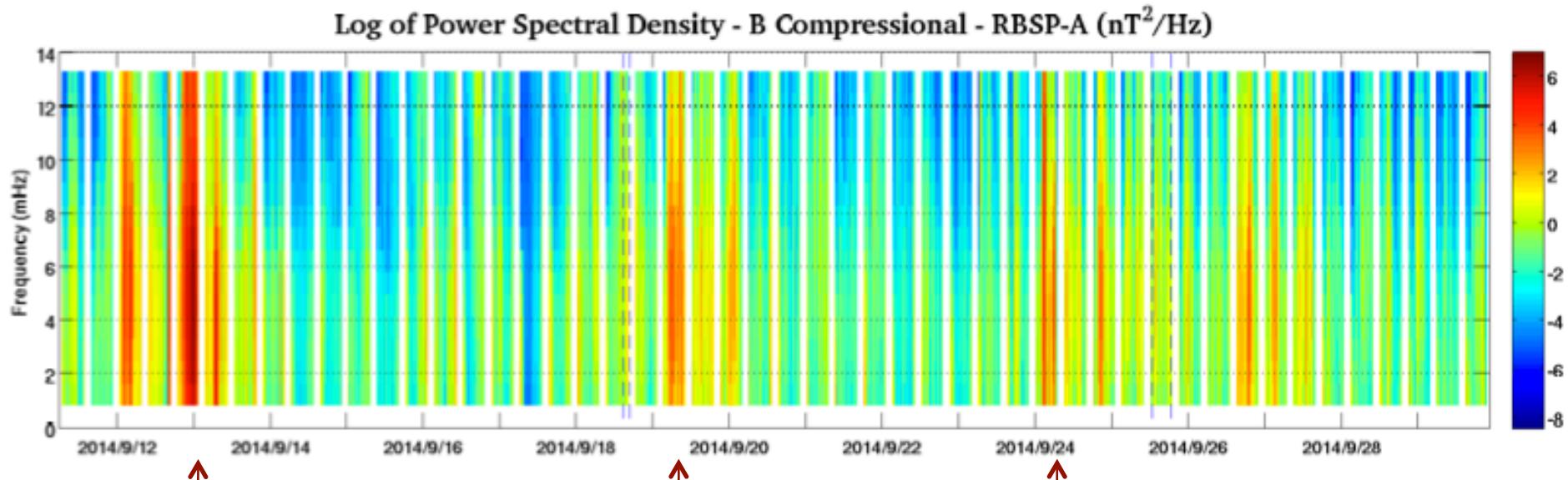
Global picture of chorus waves: POES proxy



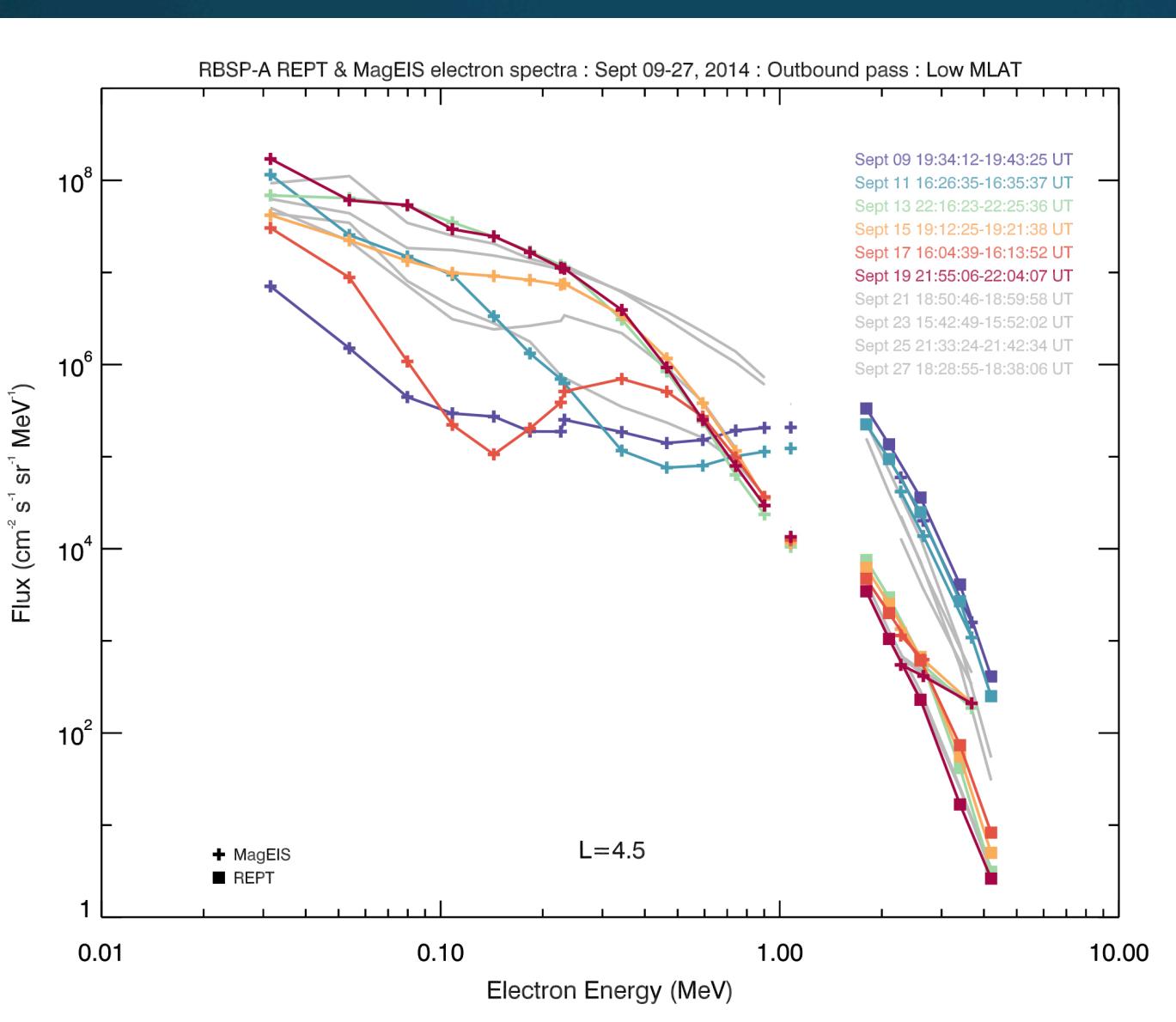
- Chorus waves as inferred by particle precipitation from POES satellites
- Virtually no chorus intensity from 13-19 September

Technique elaborated on in W. Li et al. [2013]

ULF wave power: Van Allen Probes

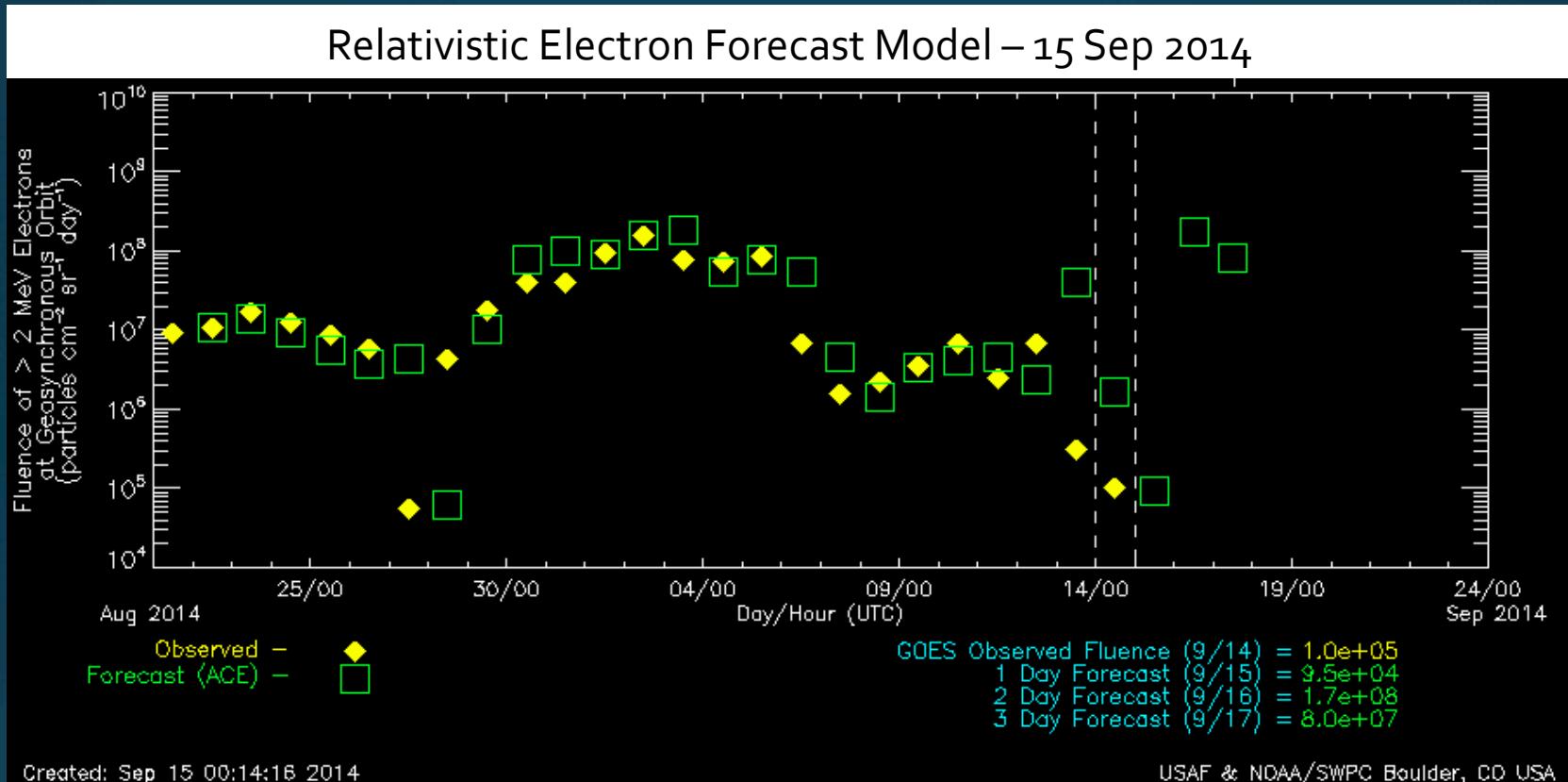


Evolution of electron energy spectra



- Cool colors denote earlier times -> warm colors denote later times
- Finally, following 23 Sept, MeV population becomes elevated once again
- Interesting transfer or cascade of energy – rocking of spectrum around a ~700 keV pivot point

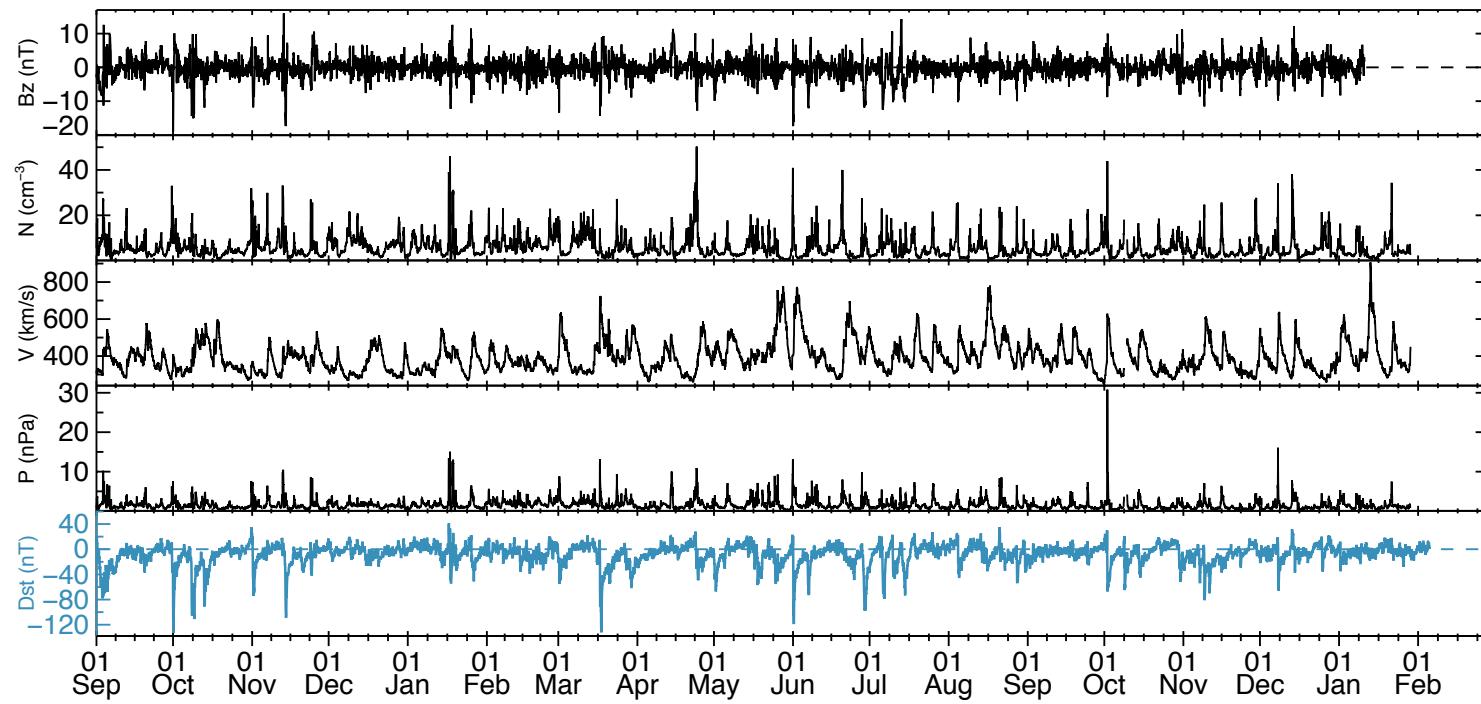
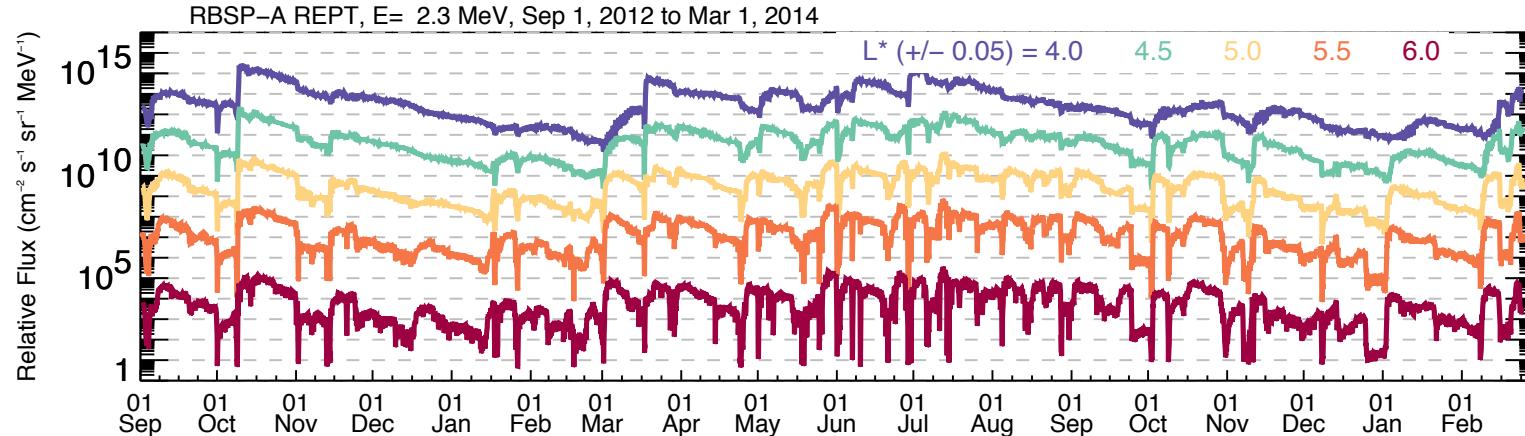
Relevance to space weather forecasting



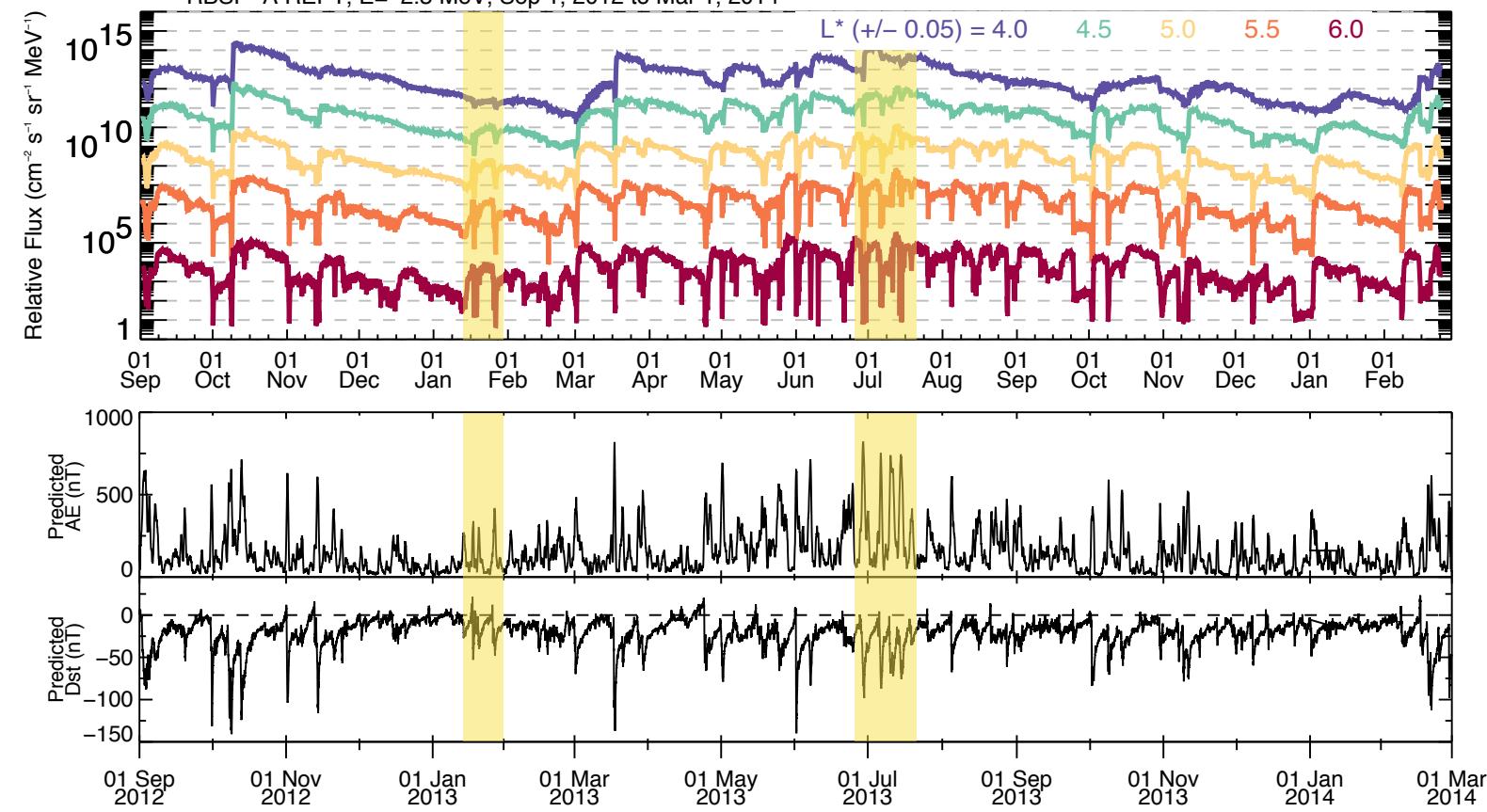
- **SWPC model (driven by SW speed) overestimates electron flux**
- It is commonly thought that increased solar wind velocity, above about 450 km/s, will result in increases in MeV electron a day or two following the solar wind velocity increase
- That is the reason the REFM predicts an increase on Sept 13 (the downward prediction trend just after that is due to the way the model adjusts for reality and the current value.)

**Further examination of seed/
source populations using Van
Allen Probes**

Effective acceleration events from Van Allen Probes mission



Effective acceleration events from Van Allen Probes mission

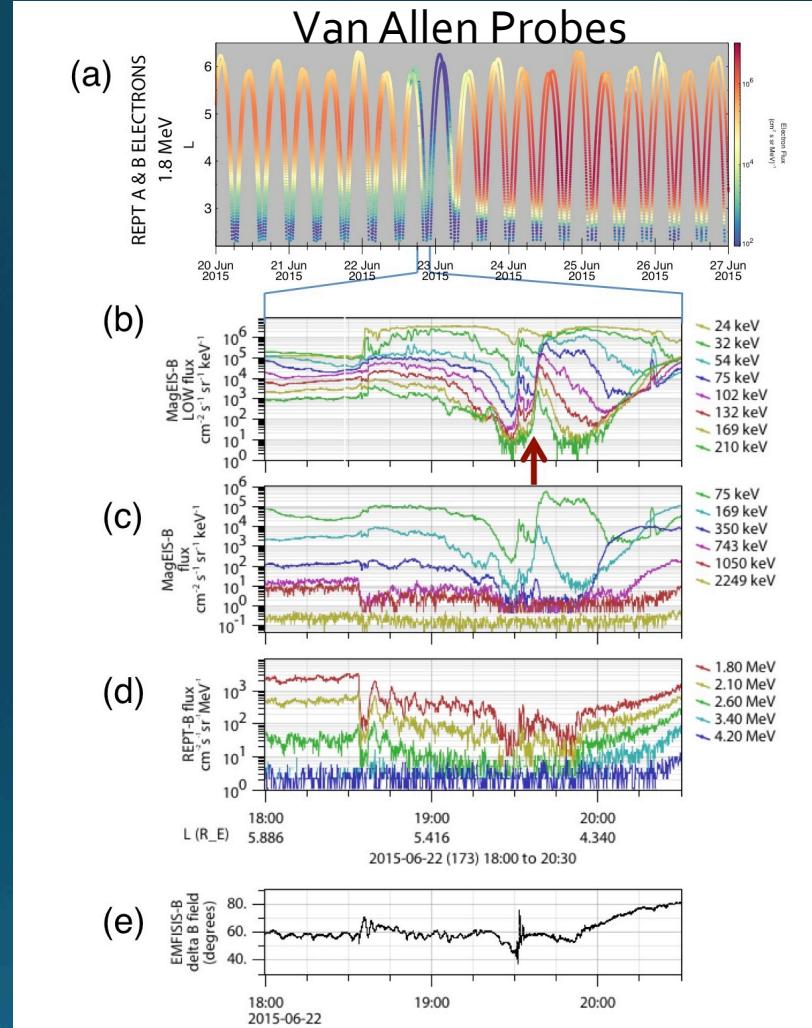
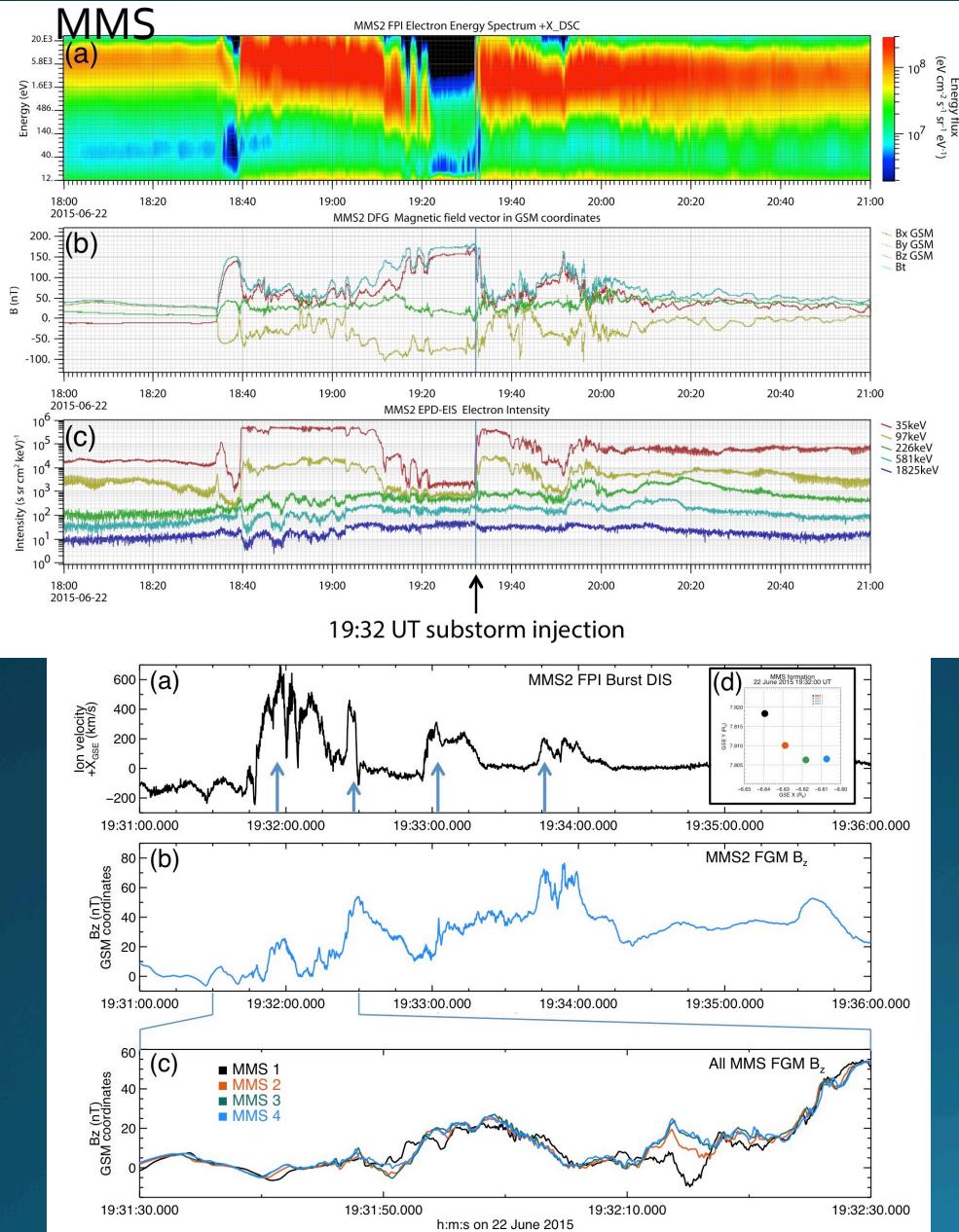


Working on developing a metric that measures the strength and duration of substorm activity (based on AE) – linear correlation will not work.

MeV electron enhancement events correlate well with enhanced AE, even without large minimum Dst.

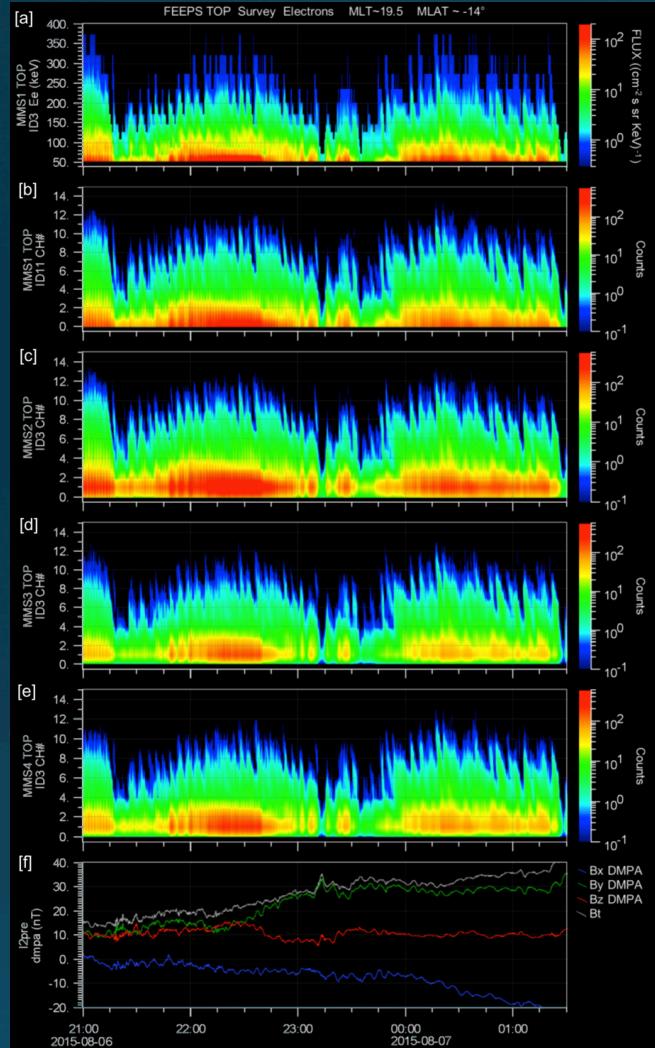
Seed & source populations: MMS studies

Examining the pathway to relativistic electrons: MMS & Van Allen Probes

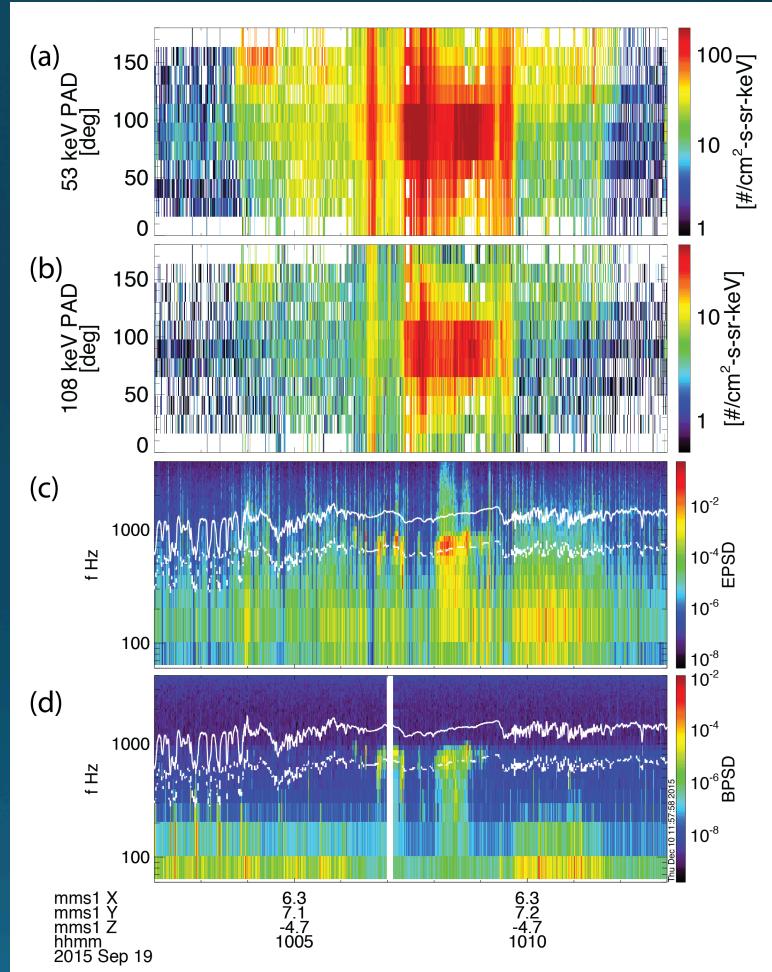


Baker et al. [2016], submitted, GRL – MMS Special Issue

MMS: Observations of seed particles in outer magnetosphere



Origin of seed
particles seen in
the inner
magnetosphere?



Summary

- Using Van Allen Probes together with existing assets like GOES (and now MMS!), we can investigate the relativistic electron accelerator mechanism in detail.
- What happens when one or more pieces are missing? The enhancement fails completely to materialize.
- Both source and seed populations are necessary for this progression to take place.
- VLF waves play a pivotal role. During what times does ULF play a major role?
- Southward IMF and substorm injections a preeminent factor in radiation belt enhancement events: implications for space weather forecasting.

